# SENSITIVITY ANALYSIS ON STEADY BIONANOFLUID BOUNDARY LAYER FLOW

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To my beloved parents and family

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# ABSTRACT

Bionanofluid is a water-based fluid consisting both nanoparticles and living motile microorganisms. Improving nanofluid instability, inducing mixing, enhancing heat and mass transfer are the benefits of adding living motile microorganisms to a nanofluid. Hence, the continuous investigation of the thermophysical properties of bionanofluid is essential in the aspect of stability and reliability. In this study, steady bionanofluid boundary layer flow near the stagnation point of a permeable shrinking surface with velocity and thermal slips conditions, moving surface with convective boundary conditions, static wedge surface and MHD permeable surface associated with multiple slips effect are modelled mathematically. The governing partial differential equations are transformed into a system of ordinary differential equations through similarity transformation. It is then solved numerically by using the shooting technique programmed in Maple18. Lastly, sensitivity analysis presented from Minitab18 is invoked to figure out the dependency of response on multivariate independent variables. The skin friction coefficient increases with suction showing positive sensitivity but decreases with slip representing negative sensitivity. Furthermore, among the independent variables, local Sherwood number is most sensitive to the Lewis number whereas the bioconvection Péclet and Schmidt numbers are the key drive parameters to the local density of motile microorganism. The theoretical study that comes with numerical results serve as an initial guideline or reference for future experimental studies and future device fabrication.

# ABSTRAK

Bio-nanobendalir adalah bendalir berasaskan air yang terdiri daripada kedua-dua nanozarah dan mikroorganisma hidup yang bergerak. Memperbaiki ketidakstabilan nanobendalir, mendorong pencampuran, meningkatkan pemindahan haba dan jisim adalah manfaat penambahan mikroorganisma hidup yang bergerak kepada nanobendalir. Oleh itu, kajian berterusan terhadap sifat termo-fizikal bio-nanobendalir adalah penting dalam aspek kestabilan dan kebolehpercayaan. Dalam kajian ini, aliran lapisan sempadan mantap bio-nanobendalir berdekatan titik genangan pada permukaan mengecut yang telap dengan keadaan gelincir halaju dan suhu, permukaan bergerak dengan keadaan sempadan perolakan, permukaan baji statik dan permukaan telap MHD yang dikaitkan dengan beberapa keadaan gelincir dimodelkan secara matematik. Persamaan menakluk pembezaan separa dijelmakan kepada sistem persamaan pembezaan biasa melalui penjelmaan keserupaan. Ia kemudian diselesaikan secara berangka dengan menggunakan kaedah tembakan yang diprogramkan di Maple18. Akhir sekali, analisis kepekaan yang dibentangkan dari Minitab18 digunakan untuk mengetahui kebergantungan respon terhadap pemboleh ubah tak bersandar multivariat. Pekali geseran kulit meningkat dengan sedutan menunjukkan kepekaan positif manakala menurun dengan gelinciran mewakili kepekaan negatif. Selain itu, di kalangan pemboleh ubah tak bersandar, nombor Sherwood setempat paling peka kepada nombor Lewis; sedangkan, nombor Péclet bio-olakan dan nombor Schmidt merupakan parameter pemacu utama kepada ketumpatan mikroorganisma bergerak setempat. Kajian teori yang datang dengan hasil berangka berfungsi sebagai garis panduan awal atau rujukan untuk kajian eksperimentasi akan datang dan selanjutnya fabrikasi peranti akan datang..

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# LIST OF SYMBOLS AND ABBREVIATIONS

**Roman Letters**

| | |
|---|---|
| $A, B, C, D$<br>$E, F, G, H$ | - Experimental parameters |
| $a, c$ | - Constants |
| $a_i, a_j$ | - Coded variables |
| $B^2$ | - Magnetic field |
| $Bi$ | - Biot number |
| $B_0$ | - Magnitude of magnetic field strength |
| $b$ | - Chemotaxis constant |
| $C$ | - Nanofluid volume fraction |
| $C_{fx}$ | - Skin friction coefficient |
| $C_w$ | - Nanofluid volume fraction at the surface |
| $C_\infty$ | - Nanofluid volume fraction far from the surface |
| $D_B$ | - Brownian diffusion coefficient |
| $D_n$ | - Diffusivity of microorganisms |
| $D_T$ | - Thermophoretic diffusion coefficient |
| $f$ | - Dimensionless velocity |
| $h_f$ | - Heat transfer coefficient |
| $\mathbf{j}$ | - Microorganism flux |

| | |
|---|---|
| $k$ | - Thermal conductivity |
| $Le$ | - Lewis number |
| $L$ | - Boundary layer thickness in the shooting program |
| $l$ | - Power-law parameter |
| $M$ | - Magnetic field parameter |
| $MS$ | - Mean squares |
| $MS-adj$ | - Adjusted mean squares |
| $m$ | - Wedge angle parameter |
| $n$ | - Number of independent variables |
| $N$ | - Concentration of microorganisms |
| $N_1$ | - Navier slip coefficient |
| $N_2$ | - Thermal slip factor |
| $N_3$ | - Nanoparticle concentration slip factor |
| $N_4$ | - Microorganism density slip factor |
| $Nn_x$ | - Local density of motile microorganism |
| $Nu_x$ | - Local Nusselt number |
| $N_w$ | - Concentration of microorganisms at the surface |
| $N_\infty$ | - Concentration of microorganisms far from the surface |
| $Nb$ | - Brownian motion parameter |
| $Nt$ | - Thermophoresis parameter |
| $P$ | - Pressure |
| $\overline{P}$ | - Number of center points |
| $Pe$ | - Bioconvection Péclet number |
| $\Pr$ | - Prandtl number |
| $q_m$ | - Wall mass flux |

| | | |
|---|---|---|
| $q_n$ | - | Wall motile microorganisms flux |
| $q_w$ | - | Wall heat flux |
| $R$ | - | Number of CCD experimental runs |
| $R^2$ | - | R-squared |
| $R^2-adj$ | - | Adjusted R-squared |
| $\mathrm{Re}$ | - | Response variable |
| $\mathrm{Re}_x$ | - | Local Reynolds number |
| $r_0$ | - | Intercept term |
| $r_i$ | - | Estimated coefficient for linear term |
| $r_{ii}$ | - | Estimated coefficient for quadratic term |
| $r_{ij}$ | - | Estimated coefficient for interaction term |
| $S$ | - | Mass flux velocity parameter |
| $Sc$ | - | Schmidt number |
| $Sh_x$ | - | Local Sherwood number |
| $SS$ | - | Sum of squares |
| $SS-adj$ | - | Adjusted sum of squares |
| $\bar{s},\bar{t},\bar{u},\bar{v},\bar{p}$ | - | Shooting parameters in the shooting program |
| $T$ | - | Temperature |
| $T_f$ | - | Convective temperature |
| $T_w$ | - | Temperature at the surface |
| $T_\infty$ | - | Temperature far from the surface |
| $U$ | - | Composite velocity |
| $u$ , $v$ | - | Velocity components in $x-$ and $y-$directions |
| $u_e(x)$ | - | Velocity near the surface where edge existed |

| | |
|---|---|
| $u_w(x)$ | - Velocity near the surface |
| $u_\infty(x)$ | - Velocity far from the surface |
| $\mathbf{v}$ | - Vector velocity |
| $\tilde{v}$ | - Chemotactic velocity |
| $W_c$ | - Maximum cell swimming speed |
| $x, y$ | - Cartesian coordinates |

**Greek Letters**

| | |
|---|---|
| $\alpha$ | - Thermal diffusivity of the nanofluid |
| $\beta$ | - Hartree pressure gradient |
| $\gamma_1$ | - Velocity slip parameter |
| $\gamma_2$ | - Thermal slip parameter |
| $\gamma_3$ | - Nanoparticle concentration slip parameter |
| $\gamma_4$ | - Microorganism density slip parameter |
| $\eta$ | - Similarity variable |
| $\eta_\infty$ | - Boundary layer thickness |
| $\theta$ | - Dimensionless temperature |
| $\lambda_1$ | - Shrinking parameter |
| $\lambda_2$ | - Velocity ratio parameter |
| $\upsilon$ | - Kinematic viscosity |
| $\rho$ | - Density |
| $\sigma$ | - Dimensionless constant |
| $\tau$ | - Ratio of effective heat capacity of nanoparticle to the base fluid |
| $\tau_w$ | - Surface shear stress |
| $\phi$ | - Dimensionless nanoparticle concentration |

| | | |
|---|---|---|
| $\varphi_1, \varphi_2,$ $\varphi_3, \varphi_4$ | - | Shooting values in the shooting program |
| $\chi$ | - | Dimensionless microorganism density |
| $\psi$ | - | Stream function |
| $\omega$ | - | Electrical conductivity |
| $\nabla$ | - | Laplacian operator |

**Superscripts**

| | | |
|---|---|---|
| $'$ | - | Differentiation with respect to $\eta$ |

**Subscripts**

| | | |
|---|---|---|
| $i$, $j$ | - | Iterations |
| $w$ | - | Corresponding value near the surface |
| $\infty$ | - | Corresponding value far from the surface |

**Abbreviations**

| | | |
|---|---|---|
| ANOVA | - | Analysis of variance |
| CCD | - | Central Composite Design |
| *DOF* | - | Degree of freedom |
| MHD | - | Magnetohydrodynamic |
| RSM | - | Response Surface Methodology |

## LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

In this chapter, there are seven different sections discussing the rationale of the study. Section 1.1 is the research background. Section 1.2 exposes the problem statement while Section 1.3 covers the research objectives. Section 1.4 states the scope of study, Section 1.5 presents the significance of study and Section 1.6 explains the thesis outline. Section 1.7 discusses the basic governing equations for the boundary layer flow problems. Lastly, Section 1.8 is a summary of the chapter.

## 1.1 Research background

Diagnostic and therapeutic purpose on human healthcare is moving to a trend of combined engineering principles and design concepts. Nanomedicine is a new medical generation where the nanomaterials/nanoparticles are designed as the diagnostic agents and therapeutic carriers. Research on metal oxide as an antimicrobial material began in the early 1950s by Sawai and his colleagues (Zhang *et al*., 2008) after nanofluid was brought to the notice (Choi and Eastman, 1995). Zinc, silver, carbon and sulfur nanoparticles are the examples of nanomaterials which have been intensively explored as the potential antibacterial agents and drugs carriers (Zhang *et al*., 2008, Salem *et al*., 2015, Dotan *et al*., 2016, and Shankar *et al*., 2018).

The studies on the bactericidal as well as the thermophysical properties of different nanoparticles are still in an on-going process by both academics and industrialists. Nanofluid that possesses good thermal conductivity and diffusivity characteristics act as smart fluid in the situations for heat and mass transfer enhancement and induce mixing. The development of commercial applications such as microfluidic devices in pharmaceutics, biological and chemical industries which use a wide variety of manufactured nanoparticles permitted the reduction of fabrication cost, diminishing the power consumption and increasing the speed and reliability of the analysis (Viktorov *et al*., 2016). Yet, some characteristics of nanoparticles require careful consideration for clinical use.

The stability of nanoparticles in the base fluid is often an issue. The phenomena of aggregating and agglomerating of nanoparticles influence the performance of nanofluid in practical conditions, i.e. reduce the efficiency and effectiveness of the rate of heat and mass transfer. Consequently, insufficient mixing arises as a challenge in designing the microfluidic devices (Rasouli *et al*., 2015). Moreover, clogging and damaging of the biological samples while passing through the microchannel is also a problem in designing the microfluidic devices (Chen *et al*., 2014 and Kang *et al*., 2018). The unstable features of nanoparticles in the base fluid limits further development of the nanofluid applications.

In order to counter the tendency of the nanoparticles, Yu and Xie (2012) reviewed the techniques for the preparation of nanofluid. It was found that the nanoparticles tend to agglomerate and cluster into a lump due to the sum of attractive and repulsive forces between the particles. Thus, methods such as use of surfactant and the surface modification method were applied. Then, Mukherjee and Paria (2013) found that the stability of a nanofluid is directly related to its electro-kinetic properties. Hence, the pH control of a nanofluid seems to have an impact in increasing the nanofluid stability. However, there appeared to be weaknesses regarding the above modifications which may limit the effectiveness of thermal conductivity of the nanofluids. Later, Kuznetsov (2010) pioneered the thought of nanofluid bioconvection in a suspension containing both nanoparticles and living motile microorganisms with the idea of inducing the convection in a nanofluid.

Swimming microorganisms such as bacteria and heavy bottom algae are then imposed into the nanofluid to overcome the instability of nanoparticles through the bioconvection phenomenon. Bioconvection is a mesoscale phenomenon in which the collective up-swimming motion of motile microorganisms induces a macroscopic motion (Pedley *et al*., 1988, Pedley and Kessler, 1992, Hill and Pedley, 2005 and Bearon and Grünbaum, 2006). The mechanism of driving up-swimming motion is intimately linked to the species of the microorganisms and responds to the external stimulus such as oxygen gradient, light intensity, chemical reaction and gravitational torques. Bioconvection is believed to help the improvement of nanofluid instability, mass transport capability in bio-microsystems such as enzyme biosensor and microscale mixing in microfluidic devices such as micromixers (Kuznetsov, 2011 and Alsaedi *et al*., 2017).

Since then, the thermophysical properties of bionanofluid have been concentrated on. The behaviours of various pertinent parameters on the skin friction coefficient, local Nusselt number, local Sherwood number and local density of motile microorganism as well as their corresponding velocity, temperature, nanoparticle concentration and microorganism density profiles were examined and analyzed. Nevertheless, previous numerical results always gave a general insight based on a particular run in a given domain. As the problem is getting more complex and realistic, more parameters are involved in the numerical algorithm and thus the numerical solutions have lost some valuable insight into the essentials of the problem.

Therefore, sensitivity analysis under the principle of Response Surface Methodology assists to provide understanding on the inherent properties reflected from the numerical solutions. Sensitivity analysis is required for relevance reasons. Firstly, sensitivity analysis refines the multivariate numerical solutions by categorizing the independent variables based on their degree of significance. Secondly, it determines which variables are more influential or have a greater impact on the output yield and identifies the key driver parameters. Finally, it provides clues for academics and industrialists in decision making concerning which variables should be altered to achieve the desirable solution on the designs model.

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